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Model Estimates of Acoustic Scattering from Schools of Large Yellowfin Tuna

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Acoustic scattering models for fish schools are used to predict scattering from large yellowfin tuna at frequencies of 50 Hz to 200 kHz. Fish of 80- to 130-cm fork length were modeled in schools of 300 to 1400 individuals. At high frequency, 2 to 200 kHz, school target strength was 0.9 to 2.5 dB. At low frequency, 50 to 1000 Hz, school target strength at resonance was highly variable, ranging from 2 to 18 dB. Just above and below resonance, scattering was complex with target strength variations of 40 dB or more caused by changes in several parameters describing school size, fish size, school depth, and packing density. At high frequency, scattering from schools of other species may be confused with tuna schools. Recommendations are made to use broadband systems at either low and high frequency in order to successfully identify tuna and to discriminate them from other fish. Additional experiments are recommended to verify model results.

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Model estimates of acoustic scattering from schools of large yellowfin tuna

Introduction

In the eastern tropical Pacific, most purse seine fishing operations search for tuna by locating dolphin schools at the surface. Tuna are often found below the dolphin. Because fisherman encircle both tuna and dolphins in purse seines, dolphin mortality is associated with this fishing method. However, tuna schools are not always associated with dolphin.

Acoustic detection and tracking of tuna schools independent of dolphin is being investigated as an alternative method of locating tuna. As part of the development of acoustic systems to detect tuna, this paper uses acoustic scattering models to predict the expected target strengths of yellowfin tuna schools. Predictions of tuna school target strength are based on acoustic models as applied to estimates of school size and behavior. Two fish school scattering models are used: one model is for low frequency, near swimbladder resonance (Feuillade and Love 1994; Feuillade et al. 1996); the other is a high frequency model, for those frequencies well above swimbladder resonance (Love 1981). Because a long range sonar is expected to have nearly horizontal propagation paths to its target, both models were used to calculate target strengths for schools insonified at horizontal aspect.

Yellowfin tuna characteristics

Several model parameters were chosen based on the characteristics of large yellowfin tuna. The equation w=0.0211L^3 , with fork length, L in cm and weight, w in gm was fit (with R^2=0.99) to tuna lengths and weights reported in Wild (1986), Table 2. This relationship was used to convert a mean school weight into the appropriate number of fish expected at a given length. It was also used in the derivation of swimbladder size for use in the low frequency model.

The low frequency model requires knowledge about swimbladders. Yellowfin tuna swimbladders are undeveloped in fish less than 40 cm (Magnuson 1973). The bladder develops and slowly increases in size as the fish grow beyond 40 cm. It was assumed that they become allometric with fish size beyond 70 cm, based on the argument that the buoyancy provided by the swimbladder must become proportional to fish mass, otherwise the tuna would become positively buoyant. For this study, large yellowfin tuna were assumed to have a swimbladder radius a = 0.051L,

based on an extrapolation of relationships obtained from Magnuson (1973). This gave a swimbladder volume of approximately 5% of fish volume for the largest tuna. Fish often have only partially inflated swimbladders (Ona 1990). To model yellowfin tuna, which are physostomes, swimbladders were assumed to provide neutral buoyancy at the sea surface and were reduced in size by compressing them, using Boyle's law, below the sea surface. This results in a slight negative buoyancy for fish 1 m below the sea surface.

Models

Low Frequency

A recently developed school scattering model was used for the low frequency scattering (Feuillade and Love 1994). This model incorporates Love's low frequency scattering model for single fish (Love 1978) as the scattering "kernel" of individual fish in a school, all uniformly oriented in the same direction. In the Love (1978) model the resonance frequency is determined mainly by swimbladder radius and hydrostatic pressure. (The swimbladder radius is the radius of a sphere of the same volume as the swimbladder.) Damping of the resonance is controlled by components representing losses due to radiative, viscous and thermal conductivity effects. Feuillade and Love (1994) determine the scattering from the school from the solution of a matrix equation. The matrix equation includes uncoupled resonance behavior of the individual swimbladders and the coupling between the swimbladders due to acoustic scattering.

In a live school, distances between neighbors will vary, as will the azimuthal and declination angles between any potential source/receiver combination and the school. The low frequency model uses a Monte-Carlo simulation to model these variations. Variations in school orientation are provided by averaging the target strength of the school over a series of "snapshot" simulations. In each snapshot the azimuthal angle of insonification is varied randomly between 0 deg and 360 deg to average over the changes of direction which are typical of a live school.

Internal school structure was also generated by a random process. Schooling fish typically adopt a somewhat uniform arrangement, which results from every fish attempting to maintain a constant distance from its neighbors (Pitcher, 1986). This results in each fish in a school occupying a volume approximately equal to its body length cubed (i.e., L^3), but this can vary significantly depending on fish behavior (Pitcher and Partridge 1979). To create schools with a realistic volume per fish and internal arrangement, we used a school volume, $V=N(cL)^3$ to calculate the volume

required for N fish, where c is the spacing between fish in body lengths and the distance between fish, $d=cL$. We created an oblate spheroid (cookie shape) of the same volume with a known height to width aspect ratio. The volume of this spheroid is $4/3\pi a^2 b$ where a is the radius and b is 1/2 the height. We randomly filled the spheroid with tuna, requiring that each new tuna added to the spheroid was at least a distance gcL away from its nearest neighbors. The factor g had to be less than one to ensure that the random filling process would successfully fill the school. Values of g of 0.7 were found to provide randomly filled schools that satisfied the equation $V=N(cL)^3$. Values of g greater than 0.8 were usually unsuccessful because as N was approached no more random places within the school could be found that would satisfy the required minimum distance to nearest neighbors.

Behavior of the low frequency model over ranges of several parameters was investigated to determine which parameters could be held constant and which would need to be examined over their full range. Parameter values are summarized in Table 1.

1) School Size. The number of fish expected in a school of mean weight 15,000 kg (C. Oliver, Pers. Comm. NMFS, S.W. Fisheries Science Center, La Jolla, CA) was determined by dividing the school weight by the expected weight of an individual fish. Numbers are: 1,400 80 cm fish; 700 100 cm fish; and 300 130 cm fish. Table 2 gives values of school radii, a, calculated for several school sizes and interfish distances. One consequence of using a mean weight of 15,000 kg is that schools of the same total mass and volume per fish give the same diameter regardless of fish size. This occurs because weight and volume per fish are both proportional to length cubed (see above).

The low frequency model becomes very computer intensive for $N > 100$. One sequence of runs at $N = 10, 30, 100$, and 300 was used to determine the validity of extrapolating from runs on a few fish (n) to a large number of fish (N) using,

$$TS_N = TS_n + 10 \log (N/n),$$

where TS_n is the target strength of the modeled school and TS_N is the target strength of the large school.

2) Aspect Ratio. School shape is expressed as the aspect ratio (ar), height/width, where schools are oblate spheroids with vertical/horizontal aspect ratios of 1/5 and 1/10. The two aspect ratios were compared.

3) Standard Deviation (S.D.) about fish length to approximate the expected variability of fish lengths within a single school. Standard deviations of 0, 5, 10 and 20% were examined.

4) Spacing (*c*), measured as the distance between fish in body lengths. Values of c=0.5, 1, 3, 10 (d=0.5L, 1L, 3L, 10L) were examined.

5) Depth. Schools were modeled at depths of 10, 30 and 100 m.

6) Fish Length. Fish of lengths of 80, 100, and 130 cm were considered. These lengths were used in (1) to determine school size.

High frequency

A high frequency model that contains empirical equations was used for frequencies well above resonance. Equations were derived from measurements of the scattering strength of fish as a function of size, orientation and acoustic frequency (Love 1977). These equations are the scattering "kernel" for each individual fish in a school. The fish are assumed to be uniformly oriented in the same direction. The model takes into account multiple scattering and attenuation effects within the school (Love 1981). The model shows that essentially all fish in small loose schools are insonified and that, as the schools get larger and denser, proportionately fewer fish are insonified. Over its range of applicability, the high frequency model is independent of frequency and depth.

Single fish have a very complex TS at high frequency as shown by measurements on many fish including several fresh and frozen yellowfin tuna (Volberg 1963). Recent theoretical modeling of the scattering process for an individual fish shows that, at high frequency, scattering varies over a range of about 5 dB for small changes in frequency and target aspect (Clay and Horne 1994). The empirical relations used in the high frequency model (Love 1971) average these variations, which are not likely to be important when sound is scattered from a large school, in which the sizes of fish and their exact alignment to the sonar beam will vary.

The high frequency model generates a probability distribution of school sizes and densities which are used to calculate an expected probability distribution of school target strengths. Rather than modify this model, it was used in its original form. Average size schools of 15,000 kg of large yellowfin tuna were modeled using average fish lengths of 80, 100, and 130 cm. The model gives a probability distribution of expected school TS as output. We chose the average of these probability distributions as representative of 15,000 kg yellowfin tuna schools.

Results

The high frequency model, 2 to 200 kHz, gave average school target strengths of 2.5, 1.6, and 0.9 dB for fish schools of 80, 100, and 130 cm length fish respectively. Attenuation effects through these small schools were small, only reducing school target strengths about 2 dB below that predicted for average target strengths for the sum of the individual fish in horizontal aspect (Love 1977). An equation for a single fish in horizontal aspect corrected for *N* fish and attenuation (-2 dB) provides a reasonable estimate for high frequency school target strengths: $TS_N=10\log(L)-68.7+10\log(N)-2$.

At low frequency, scattering from the fish schools is more complex than at high frequency. Fig. 1 is used to demonstrate overall differences between the single fish model (bold dots) and the school model (curves). It also shows the effects of increasing the number of fish in the school (solid and dashed curves). Results in Fig. 1 are normalized to the TS of one fish using $TS_1=TS_N-10\log N$. Two effects are important. First, the resonance peak of the school model is lower in frequency and is at a lower level than the single fish model. It shifts from 220 Hz to about 170 Hz. This is the result of the resonant coupling between the individual bladders in the school. Second, peaks and troughs are evident off resonance. For example, a peak at 500 Hz and a trough at 100 Hz. These are coherent interference effects resulting from the coherent addition of in-phase and out-of-phase scattering from the multitude of fish in the school. They are most evident at low frequency and converge to the single fish model at high frequency.

Fig. 1 also shows that increasing the number of fish in the school results in stronger coupled resonance effects in the larger schools. This results in a decrease in the individual TS at resonance and shifts it lower in frequency. Changes from N=10 to N=300 are consistent. This consistency is used to argue that the multiple scattering effects become fully apparent at N of 100 and 300. Consequently we use runs of 100 fish and scale the results for schools of 300, 700 and 1,400 fish. This assumption could introduce an overestimate of the school target strength at resonance by about 3 dB. However, this error is negligible compared to the overall uncertainty introduced by the coupled resonance and multiple scattering effects, phenomena predicted by modeling but as yet untested.

Results of evaluating the two aspect ratios are shown in Fig. 2. The ratios 1/5 and 1/10 only produce subtle differences in the shapes of the scattering curves. A slight shift downward for the more spherically shaped school was evident, this was probably because of the greater proportion of fish in close proximity to one another in this shape. An

aspect ratio of 1/5 was used for the remainder of the analysis as it represented the less extreme school formation.

Increasing the S.D. about fish L resulted in a broadening of the resonance peak (Fig. 3), but no other significant effects. This broadening was caused by a greater range in the sizes and hence resonance peaks of the individual bladders. These effects were not sufficient to alter any of the effects of multiple scattering below or above resonance. The downward shift in resonance from the single fish to the school and the occurrence of coherent interference bumps near 500 Hz remain regardless of the choice of S.D. The intermediate S.D. of 10% was chosen to represent schools for the other parameters and in the subsequent modeling effort.

Four levels of spacing produced noticeable effects. In Fig. 4 the most compact spacing (d=0.5 L) shows the greatest shift in resonance (210 Hz to 170 Hz) and the strongest coherent interference effects above resonance (dip at 600 Hz). Less compact spacing shows more subtle effects, with the least compact, (d=10 L) giving a curve closely approaching that of the single fish model. We choose the intermediate spacing of d=1L as a likely occurrence in natural schools and used it in determining the behavior of the other parameters.

Subsequent modeling of length and depth were carried out with school size, aspect ratio, bladder variability, and fish spacing fixed (Table 1). The modeling of three tuna lengths and 3 depths is demonstrated in a 9 panel figure (Fig. 5), which shows both the decrease in resonance with schools of larger sized fish and the resultant increase in resonance frequency with depth. Swimbladder compression also results in smaller target strengths at greater depth. The decrease in resonance frequency with greater tuna length for 30 m depth is also shown in Fig. 6, and the increase in resonance with increasing depth is shown for 100 cm tuna in Fig. 7. Overall, highly variable target strengths and resonance frequencies can occur depending on school depth, fish length, coupled resonance, and interference effects. Target strengths output from the low frequency model were linearly averaged for 1/3rd octaves from 50 Hz to 1000 Hz. A summary is given in Table 3. Maximum levels at resonance ranged from 2 to 18 dB.

Discussion

Several characteristics of the scattering from the yellowfin tuna schools affect the choice of frequency and bandwidth for an active sonar designed to detect tuna. Broadband systems appear advantageous at both low and high frequencies, however the reasons differ.

Foremost, at low frequency (50 to 1000 Hz), scattering from the yellowfin tuna schools will be complex. Coupled resonance and coherent interference effects combine to produce a wide range of expected school target strengths at any particular frequency. Differences as high as 40 dB are expected due to changes in several parameters describing school size, depth, and fish spacing. For example, a fairly compact school of 100 cm tuna with d=1.0L at 30 m depth would have a TS of 6 dB at 200 Hz. If this school became more dispersed and moved to 100 m depth it would have a TS of -19 dB at 200 Hz. For these reasons, scattering over a narrow frequency band would be difficult to interpret.

At low frequency a broadband sonar (50 Hz to 2 kHz) could take advantage of the unique shape of the low frequency resonance for target identification. If the depth of the target is known, the resonance frequency can provide diagnostic information on fish size. The characteristics of coupled resonance and coherent interference "bumps" can provide information on the spacing of fish within the school. These diagnostic features have been used in the interpretation of broadband low frequency scattering data for schools of anchovy and hake (Nero and Feuillade 1995; Feuillade et al. 1996) and the modeling shown in this study demonstrates that it could work for tuna schools.

At high frequency (2 kHz to 200 kHz) the scattering is predicted to be simple in relation to school parameters, with little change in TS due to school depth and fish spacing. One would expect a narrow band system to work well. However, fish smaller than tuna that resonante at 2-5 kHz (Nero 1992) may be false targets for a system searching for large yellowfin. Large schools of anchovy, sardine, mackerel and juvenile tuna could have target strengths as strong as or greater than schools of large tuna. At particular narrow band frequencies these small fish may be difficult to distinguish from the large tuna. However, the strong frequency dependence of these targets at 2-5 kHz (because of swimbladder resonance) could be used by a broadband high frequency system to discriminate them from large tuna. Behavioral cues or the use of echo characteristics may also aid in high frequency target discrimination.

Recommendations

Schools of large yellowfin tuna offer the best target information over a broadband low frequency range (100-1000 Hz). This conclusion is based on the expected resonance effects. At high frequency (2-5 kHz) a broadband range is also recommended in order to discriminate schools of large tuna from schools of small pelagic fish which will be resonant scatterers at these frequencies.

Variation in school mass beyond the "average" school of 15,000 kg would certainly increase the range in expected school TS beyond that examined in this study. Further modeling should include a realistic probability distribution of school sizes.

This modeling study has led to the identification of several research needs. Measurements of the swimbladder characteristics of large yellowfin tuna are recommended. The buoyancy of fresh dead animals at sea and estimates of their swimbladder volume would be a vast improvement over the inferred value used in this study. Validation of the low frequency and high frequency models and target strength predictions are also recommended. The target strength of yellowfin tuna has been measured at high frequency (Volberg 1963) but not at low frequency. Low and high frequency school measurements should be made on live schools. High frequency measurements are feasible. Low frequency measurements are difficult considering the unwieldy character of low frequency sound sources and receivers and the highly mobile nature of tuna schools.

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Table 1. School and fish parameters examined. Rows are of parameters evaluated at for the values given in the third column. Subsequent columns give the values of parameters held constant during the evaluation.

Parameter		Evaluated At:	N	ar	bv	d	z	L
School Size (ind)	N	10,30,100,300	-	1/5	0.1	1	30	100
Aspect Ratio	ar	1/5,1/10	100	-	0.1	1	30	100
Bladder Var.	bv	0.5,0.1,0.2	100	1/5	-	1	30	100
Spacing	d	0.5,1,3,10	100	1/5	0.1	-	30	100
Depth (m)	z	10,30,100	100	1/5	0.1	1	-	100
Fish Length (cm)	L	80,100,130	100	1/5	0.1	1	30	-

Table 2. School radii (m), for model schools with a 1/5 aspect ratio.

Interfish Distance (Body Lengths)	Number of Fish	Body Length (m) 0.8	1	1.3
0.5	10	0.9	1.1	1.5
	30	1.3	1.6	2.1
	100	2.0	2.5	3.2
	300	2.8	3.6	4.6
	700	3.8	4.7	6.1
	1400	4.7	5.9	7.7
1	10	1.8	2.3	3.0
	30	2.6	3.3	4.3
	100	3.9	4.9	6.4
	300	5.7	7.1	9.2
	700	7.5	9.4	12.2
	1400	9.5	11.9	15.4
3	10	5.5	6.9	8.9
	30	7.9	9.9	12.9
	100	11.8	14.8	19.2
	300	17.0	21.3	27.7
	700	22.6	28.3	36:7
	1400	28.5	35.6	46.3
10	10	18.3	22.9	29.7
	30	26.4	33.0	42.8
	100	39.4	49.2	64.0
	300	56.8	71.0	92.3
	700	75.3	94.2	122.4
	1400	94.9	118.7	154.3

Table 3a. Low frequency target strength estimates for very dense schools of yellowfin tuna. Values are linear averages of 1/3 octave bands.

		Interfish Distance = 0.5 L								
		10 m depth			30 m depth			100 m depth		
		Number of Fish			Number of Fish			Number of Fish		
		1400	700	300	1400	700	300	1400	700	300
Frequency Band (Hz)		Fish Length (cm)			Fish Length (cm)			Fish Length (cm)		
Center	Lower-Upper	80	100	130	80	100	130	80	100	130
50	45-56	5	10	17	-10	-7	-3	-28	-26	-23
63	56-71	12	16	13	-5	-3	2	-24	-22	-19
80	71-90	18	16	4	-2	1	6	-21	-20	-17
100	90-112	16	6	2	3	5	9	-18	-17	-16
125	112-140	2	2	2	7	8	13	-16	-16	-18
160	140-180	2	3	0	9	11	2	-14	-19	-20
200	180-224	3	0	-2	11	2	-1	-16	-20	-10
250	224-280	2	-2	-5	-1	0	-4	-20	-10	-7
315	280-355	0	-5	-9	0	-4	-9	-9	-7	2
400	355-450	-3	-7	-12	-2	-7	-13	-4	2	0
500	450-560	-6	-10	-10	-5	-10	-11	2	-1	-6
630	560-710	-8	-10	-8	-8	-11	-9	1	-5	-9
800	710-900	-7	-5	-4	-8	-6	-5	-3	-5	-5
1000	900-1120	-5	-3	-3	-6	-4	-4	-4	-4	-6

Table 3b. Low frequency target strength estimates for moderately dense schools of yellowfin tuna. Values are linear averages of 1/3 octave bands.

		Interfish Distance = 1.0 L								
		10 m depth			30 m depth			100 m depth		
		Number of Fish			Number of Fish			Number of Fish		
		1400	700	300	1400	700	300	1400	700	300
Frequency Band (Hz)		Fish Length (cm)			Fish Length (cm)			Fish Length (cm)		
Center	Lower-Upper	80	100	130	80	100	130	80	100	130
50	45-56	1	4	6	-12	-11	-11	-31	-29	-29
63	56-71	5	7	11	-10	-9	-15	-28	-28	-34
80	71-90	8	9	11	-8	-9	-14	-27	-29	-39
100	90-112	10	11	4	-10	-12	-4	-29	-34	-28
125	112-140	14	2	1	-14	-4	3	-39	-29	-30
160	140-180	5	1	-3	-3	3	6	-27	-25	-24
200	180-224	2	-4	-7	3	6	2	-24	-21	-18
250	224-280	-4	-7	-7	3	2	-4	-24	-20	-10
315	280-355	-8	-6	-7	-1	-3	-7	-17	-13	3
400	355-450	-6	-5	-4	-5	-5	-5	-8	3	8
500	450-560	-4	0	-2	-4	-1	-3	3	6	2
630	560-710	0	-1	-4	-1	-2	-6	8	4	-5
800	710-900	0	2	-1	-1	0	-2	4	1	-3
1000	900-1120	0	1	-2	-1	-1	-3	0	-1	-5

Table 3c. Low frequency target strength estimates for very loose schools of yellowfin tuna. Values are linear averages of 1/3 octave bands.

Frequency Band (Hz)		Interfish Distance = 3.0 L								
		10 m depth			30 m depth			100 m depth		
		Number of Fish			Number of Fish			Number of Fish		
		1400	700	300	1400	700	300	1400	700	300
		Fish Length (cm)			Fish Length (cm)			Fish Length (cm)		
Center	Lower-Upper	80	100	130	80	100	130	80	100	130
50	45-56	-16	-16	-14	-30	-29	-31	-48	-47	-50
63	56-71	-12	-15	0	-26	-31	-23	-44	-50	-42
80	71-90	-13	-4	11	-28	-23	-17	-47	-42	-36
100	90-112	-3	9	12	-21	-17	-8	-41	-37	-30
125	112-140	5	11	8	-17	-12	5	-37	-33	-23
160	140-180	9	7	4	-11	2	12	-33	-23	-18
200	180-224	10	4	-1	3	11	7	-23	-19	-15
250	224-280	6	2	-1	13	10	1	-18	-13	-9
315	280-355	3	1	0	9	4	0	-13	-8	4
400	355-450	1	0	0	4	0	-1	-7	0	10
500	450-560	2	0	-1	2	0	-3	3	10	3
630	560-710	2	0	0	1	-2	-1	10	6	0
800	710-900	2	0	-1	1	-1	-3	7	0	-3
1000	900-1120	2	0	-1	0	-2	-3	2	-2	-4

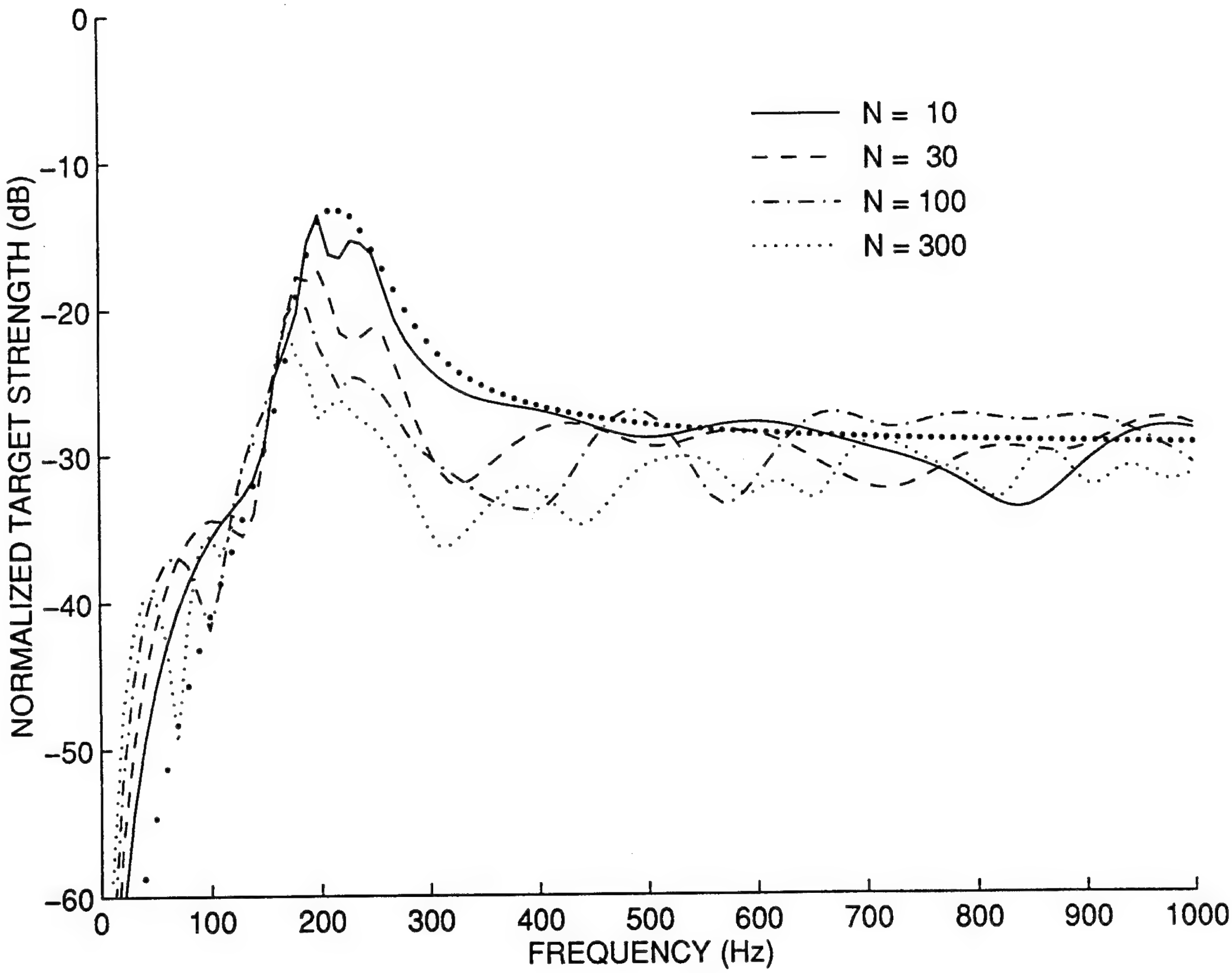

Figure 1. Normalized target strength for one fish in schools of increasing number of individuals (N= 10, 30, 100, and 300) compared to the single fish model (large dots).

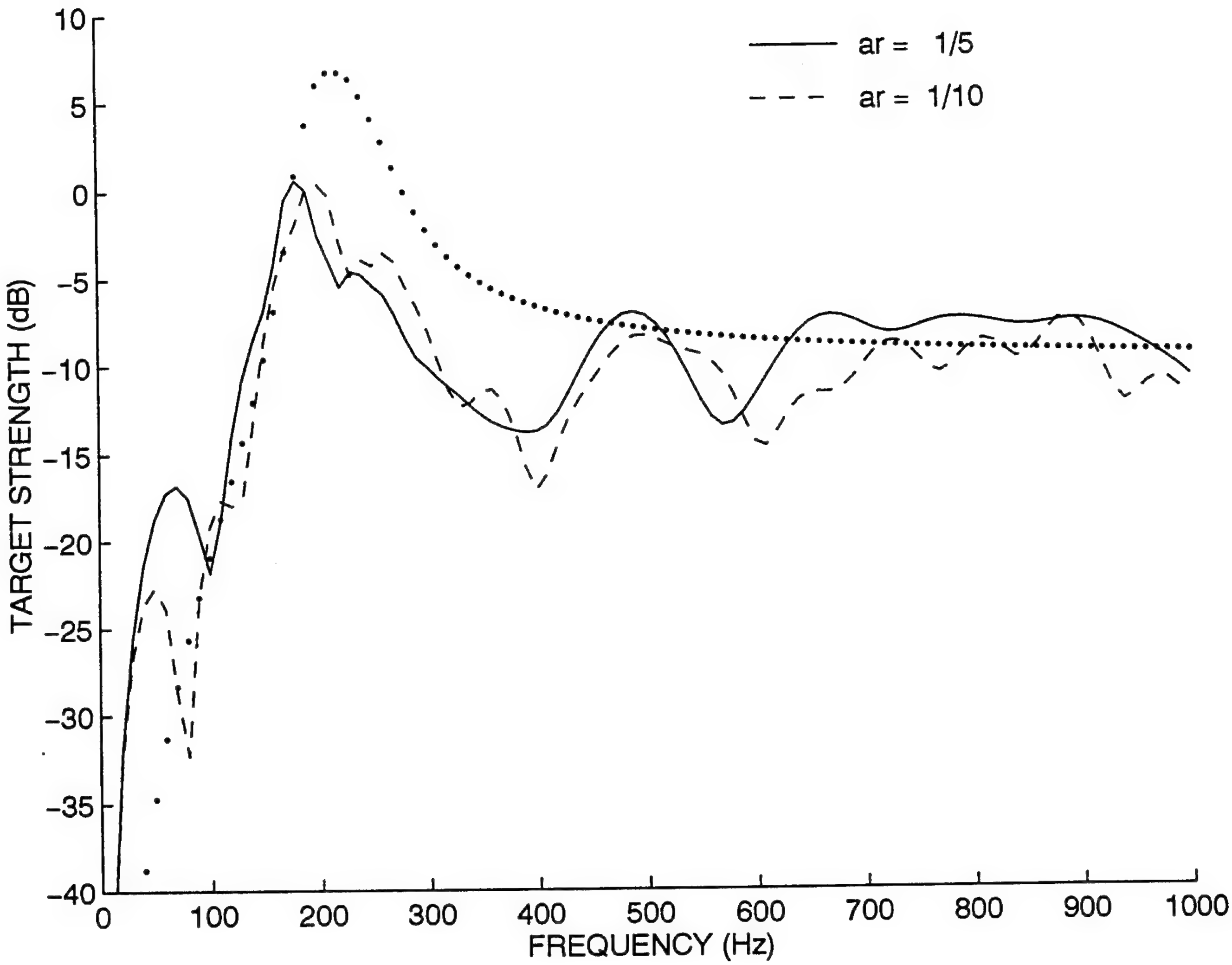

Figure 2. Comparison of school targets strengths for school aspect ratios of 1/5, 1/10, and the single fish model (large dots).

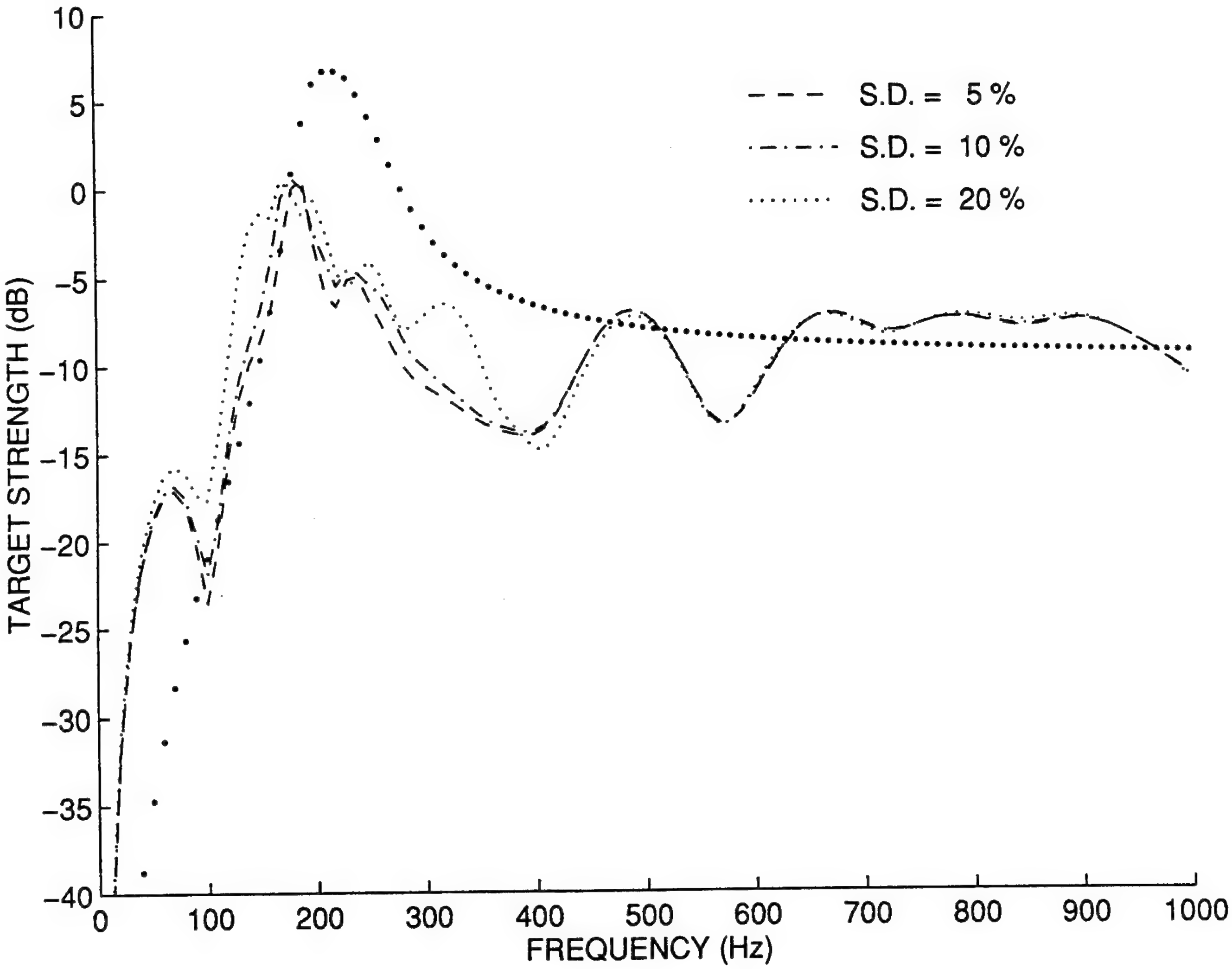

Figure 3. Comparison of school target strengths for schools with the Standard Deviation (S.D.) of fish length at 5, 10, and 20 % in comparison to the single fish model (large dots).

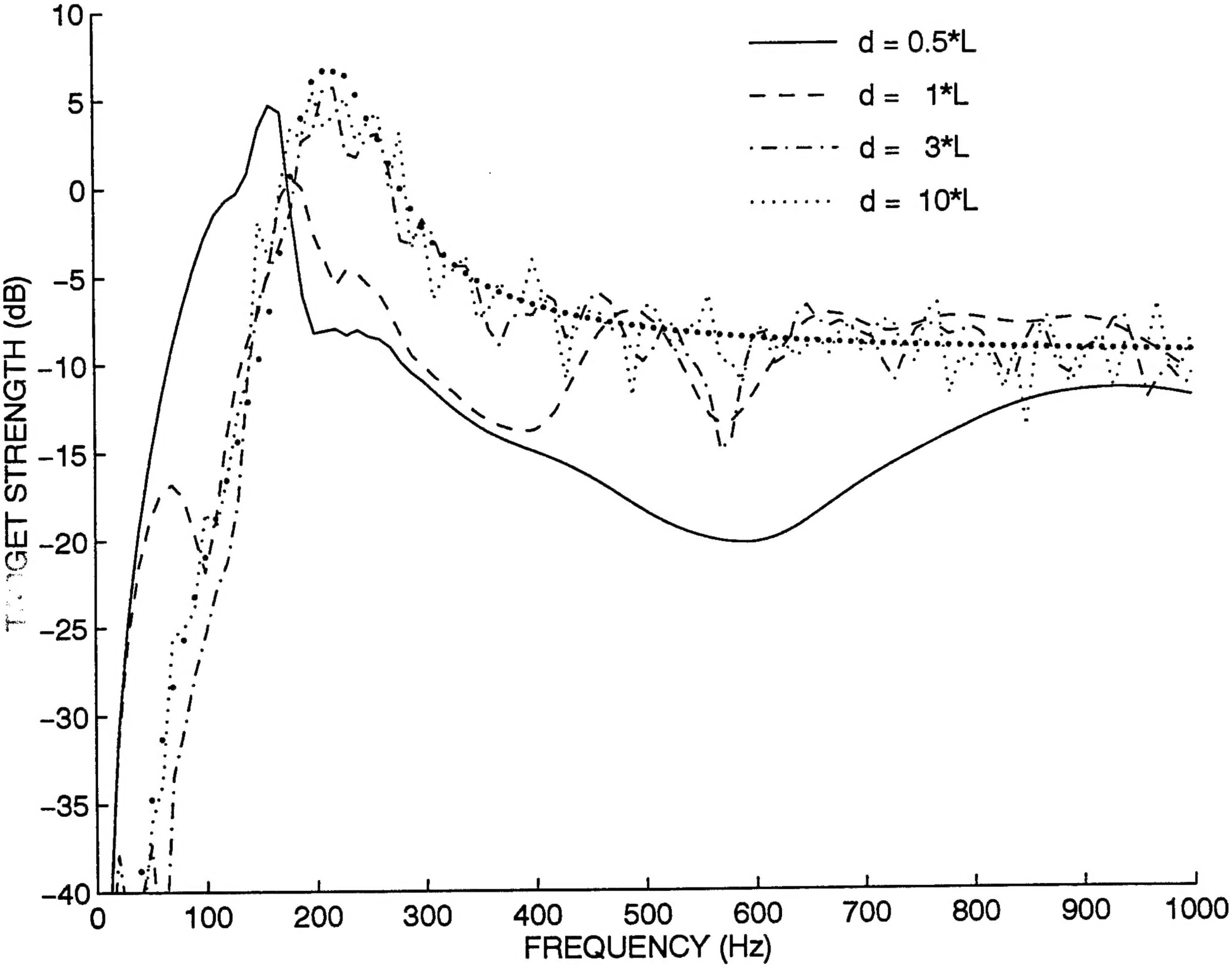

Figure 4. Comparison of school target strengths for schools at fish spacings of 0.5, 1, 3, and 10 body lengths in comparison to the single fish model (large dots).

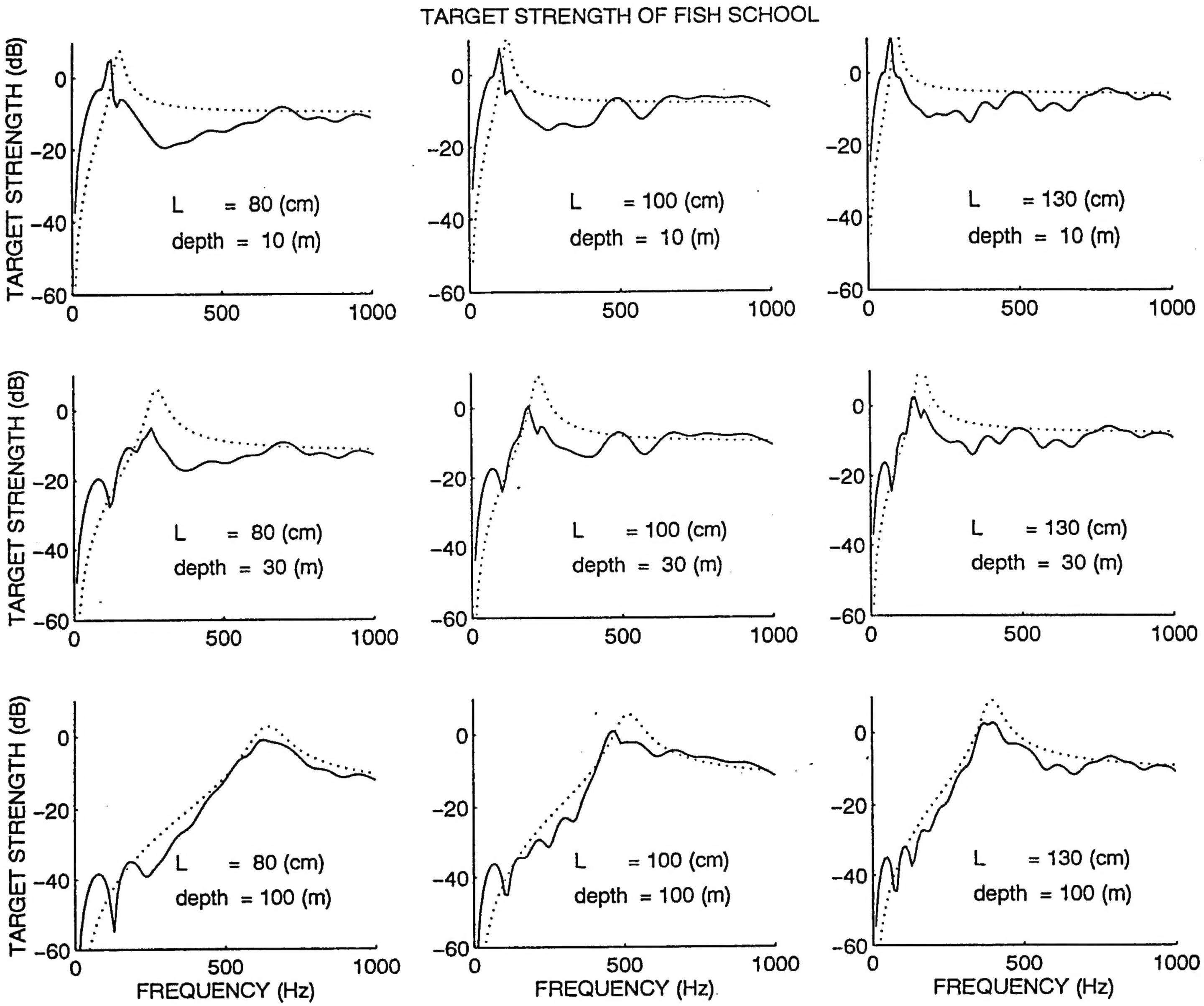

Figure 5. The effect of school depths of 10, 30, and 100 m and fish total length, 80, 100, and 130 cm on school target strength. In all plots the single fish model is shown as a dotted curve.

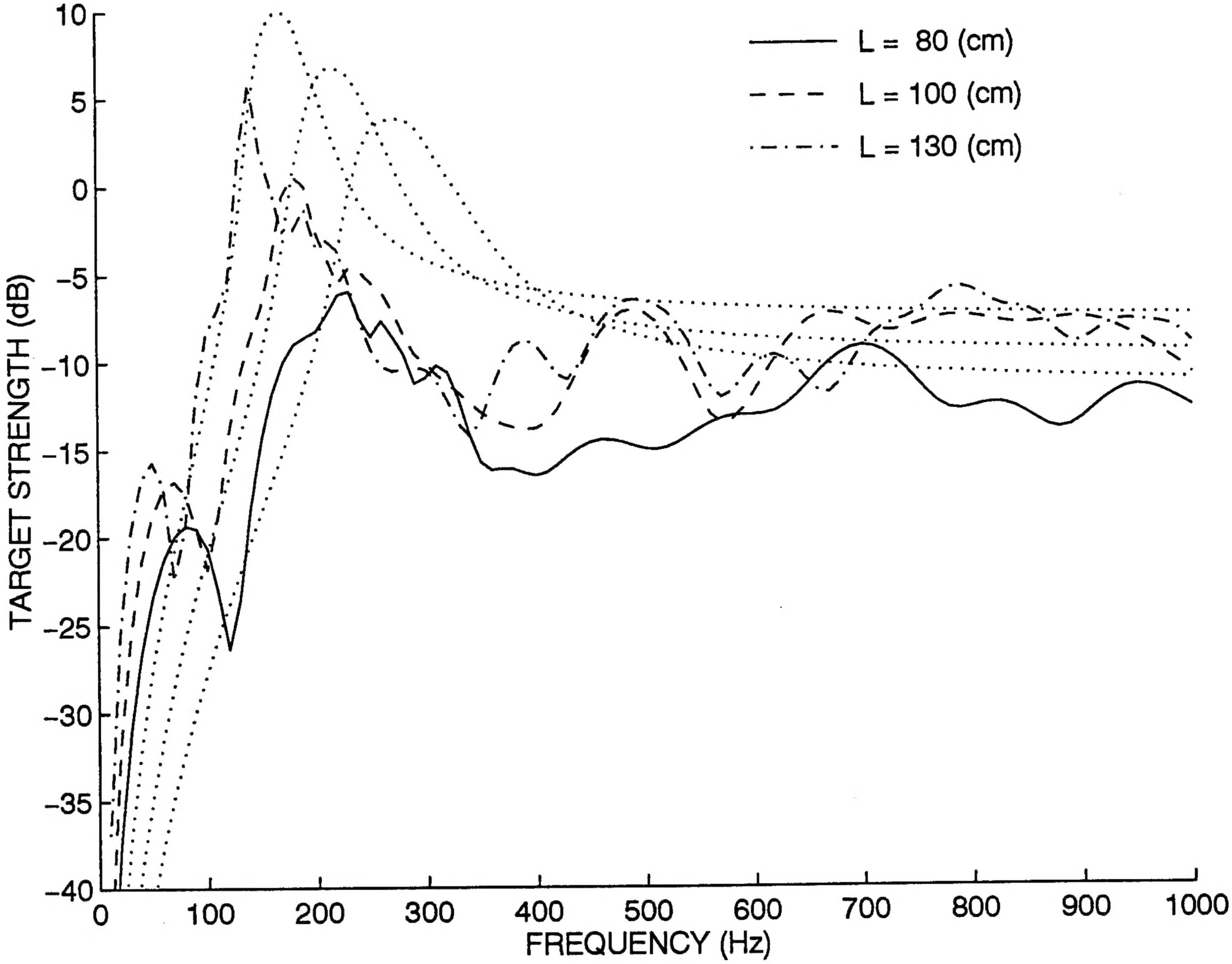

Figure 6. Comparison of school targets strengths for schools of fish of 80, 100, and 130 cm at 30 m depth in comparison to the single fish model (large dots).

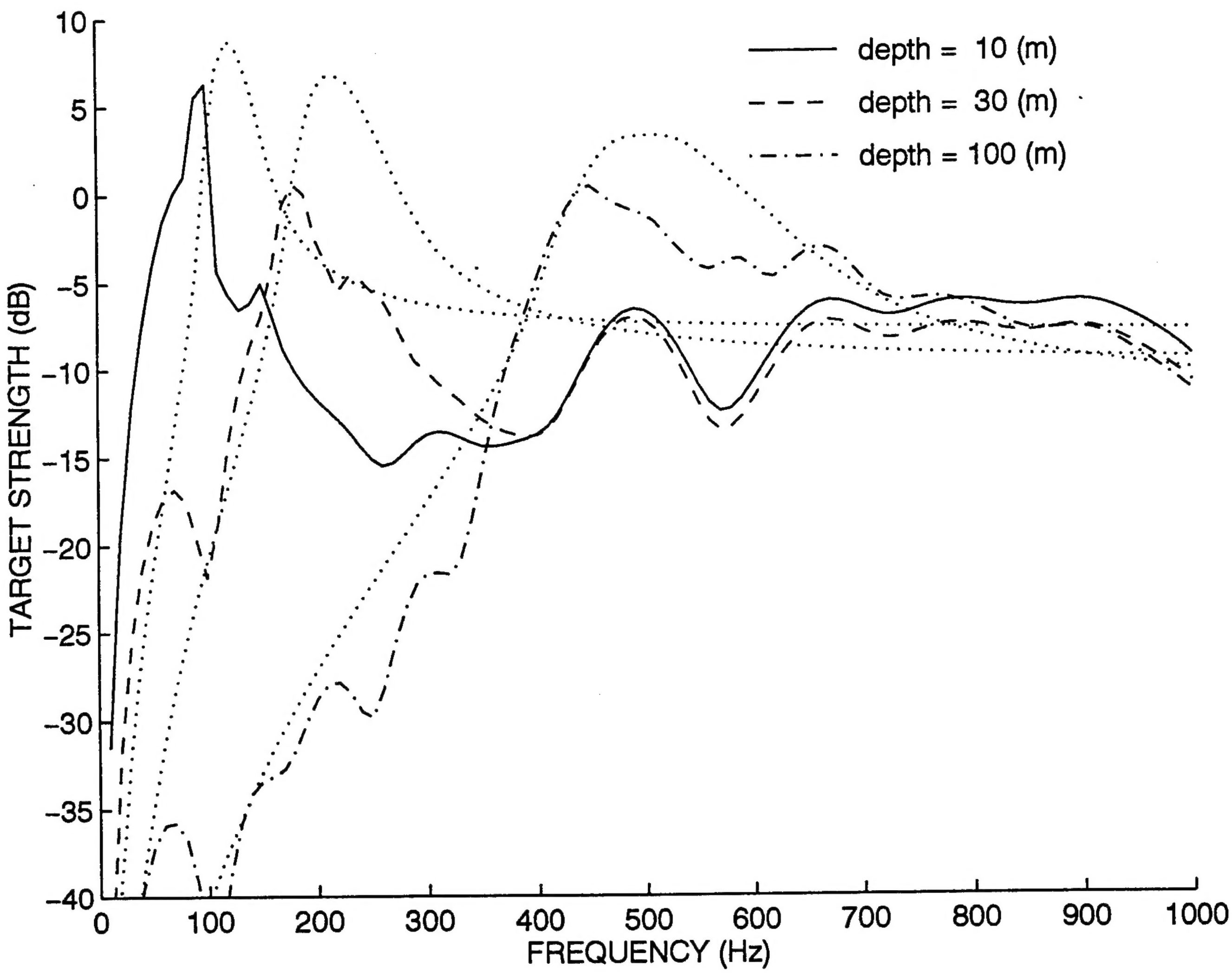

Figure 7. Comparison of school targets strengths for schools of 100 cm fish at 0.5, 10, 30, and 100 m depth in comparison to the single fish model (large dots).